Mobile Communication Systems

Spread Spectrum

Ch13: Wireless Communications (Prof. Goldsmith)

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Spread Spectrum

- Spread spectrum is a technique that increases signal bandwidth beyond the minimum necessary for data communication.
- Reasons:
  - hide a signal below the noise floor (useful for military)
  - mitigates the performance degradation due to ISI
  - can provide coherent combining of different multipath components (RAKE receiver)
  - allows multiple users to share the same signal bandwidth
  - useful for location and timing acquisition
- Widespread in military and commercially in Cordless phones
- Used in Cellular (IS-95/3G) and 2nd Gen. WLAN

Spread Spectrum Principles

- A modulation method applied to digitally modulated signals that increases the transmit signal bandwidth to a value much larger than is needed to transmit the underlying information bits
- Different from coding/frequency modulation
- The following three properties are needed for a signal to be spread spectrum modulated:
  - The signal occupies a bandwidth much larger than is needed
  - The spread spectrum modulation is done using a **spreading code (independent of data)**
  - De-spreading at the receiver is done by correlating the received signal with a synchronized copy of the spreading code

Spread Spectrum Principles

- Suppose a set of linearly independent signals $s_i(t),\ i = 1,2,\ldots,M$ of bandwidth B and time duration T such that

$$s_i(t) = \sum_{j=1}^{N} s_{ij}\phi_j(t)\ , \qquad 0 \le t < T$$

- the minimum number of basis functions needed to represent these signals is M ≈ 2BT
- Hence, to embed these signals into a larger dimensional space, we chose N >> M
- Suppose we generate the signals $s_i(t)$ using **random sequences** so that the sequence of coefficients s_{ij} are chosen based on a random sequence generation where each coefficient has mean zero and variance E_s/N
- Thus, the signals $s_i(t)$ will have their energies uniformly distributed over the signal space of dimension *N*

Spread Spectrum Principles

- Consider an interference or jamming signal within this signal space

$$I(t) = \sum_{j=1}^{N} I_j \phi_j(t)$$

with total energy $\int_0^T I^2(t) = \sum_{j=1}^{N} I_j^2 = E_J$

- If the receiver uses an *M* branch structure where the *i*th branch correlates the received signal $x(t) = s_i(t) + I(t)$ with $s_i(t)$
- The output of the correlator in the *i*th branch of the receiver is then

$$x_i = \int_0^T x(t)s_i(t)dt = \sum_{j=1}^{N} s_{ij}^2 + I_j s_{ij}$$

- the signal-to-interference (SIR) power ratio of this signal is

$$SIR = \frac{E_s}{E_j} \times \frac{N}{M}$$

Spread Spectrum Principles

- By spreading the interference power over a larger dimension *N* than the required signaling dimension *M*, the SIR is increased by G = N/M, where *G* is called the **processing gain**.
- In practice spread spectrum systems have processing gains on the order of 100-1000 (note N $\approx 2B_sT$ or G = B_s/B)
- Spread spectrum is typically implemented in one of two forms:
  - **Direct sequence** (DS)
  - **Frequency hopping** (FH)

Direct sequence spread spectrum (DSSS) modulation

- the modulated data signal $s(t)$ is multiplied by a wideband **spreading signal or code** $s_c(t)$
- $s_c(t)$ is constant over a time duration T_c and has amplitude equal to 1 or -1
- The spreading code bits are usually referred to as **chips**, and $1/T_c$ is called the chip rate
- The bandwidth $B_c \approx 1/T_c$ of $s_c(t)$ is roughly $B_c/B \approx T_s/T_c$ times bigger than the bandwidth B of the modulated signal $s(t)$, and the number of chips per bit, T_s/T_c, is an integer approximately equal to G, the processing gain of the system.

Direct sequence spread spectrum (DSSS) modulation (BPSK)

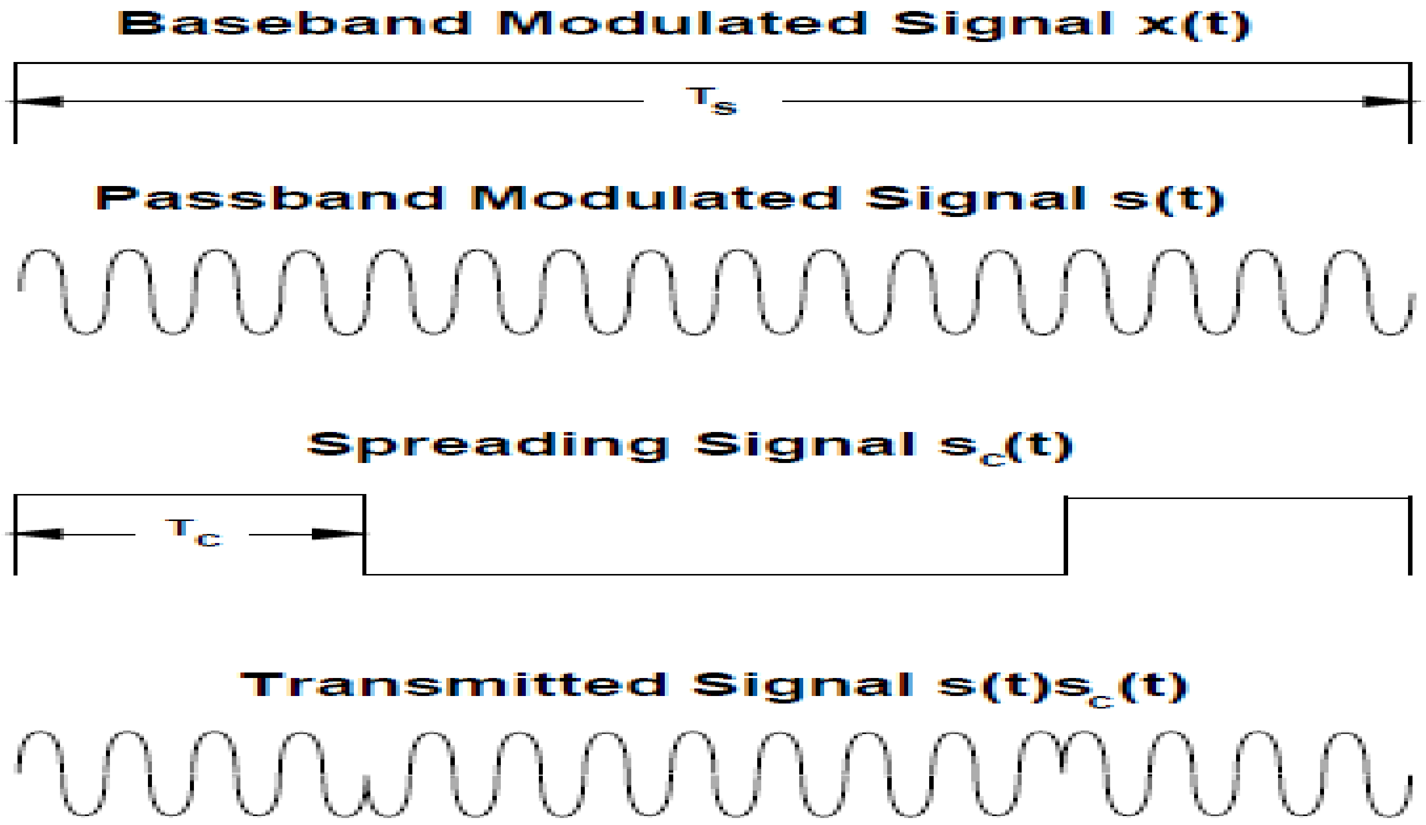

Figure 13.1: Spreading Signal Multiplication

Direct sequence spread spectrum (DSSS) modulation

- For an AWGN channel the received spread signal is $s(t)s_c(t) + n(t)$.
- If the receiver multiplies this signal by a synchronized replica of the spreading signal, this yields $s(t)s_c^2(t) + s_c(t)n(t)$.
- Since $s_c(t) = \pm 1$, $s_c^2(t) = 1$→received is $s(t)$+$n'(t)$
- Moreover $n'(t) = n(t)s_c(t)$ has approximately the same statistics as $n(t)$ if $s_c(t)$ is zero mean and sufficiently wideband
- Spreading and despreading have no impact on signals transmitted over AWGN channels
- Spreading and despreading have tremendous benefits when the channel introduces narrowband interference or ISI

Narrowband interference rejection

- **Time domain**
- $s(t)s_c(t)$

- **Frequency domain**
- **At Tx:** $S(f) * S_c(f)$
- **At Rx:** $I(f) * S_c(f)$ **(**despreading**)**

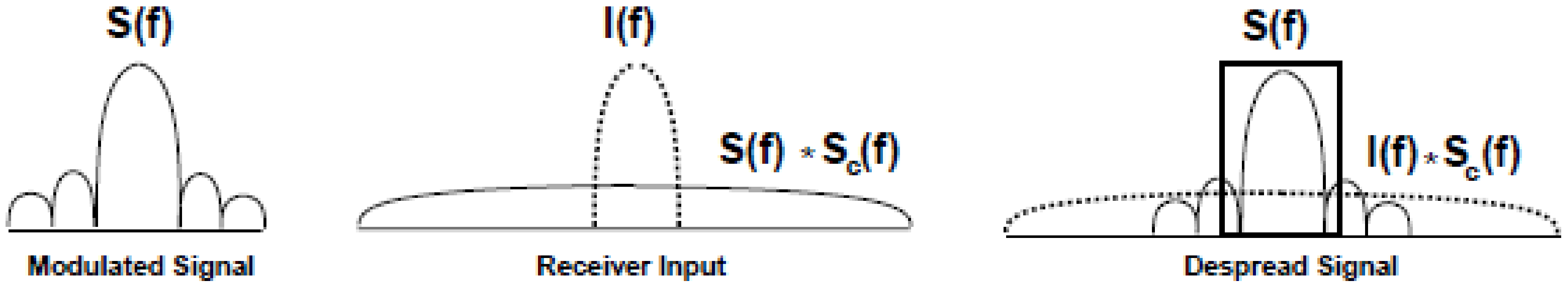

Figure 13.2: Narrowband Interference Rejection in DSSS.

ISI rejection

- $s(t)s_c(t)$
- $h(t) = \alpha\delta(t) + \beta\delta(t-\tau)$
- At Rx: $[s(t)s_c(t)]* h(t)$

= $\alpha s(t)s_c(t) + \beta s(t-\tau)s_c(t-\tau)$

After despread:

$$\alpha s(t)s_c^2(t) + \beta s(t-\tau)s_c(t-\tau)s_c(t)$$

- $H(f) = \alpha + \beta e^{-j2\pi f\tau}$
- At Rx: $H(f)[S(f) * S_c(f)]$

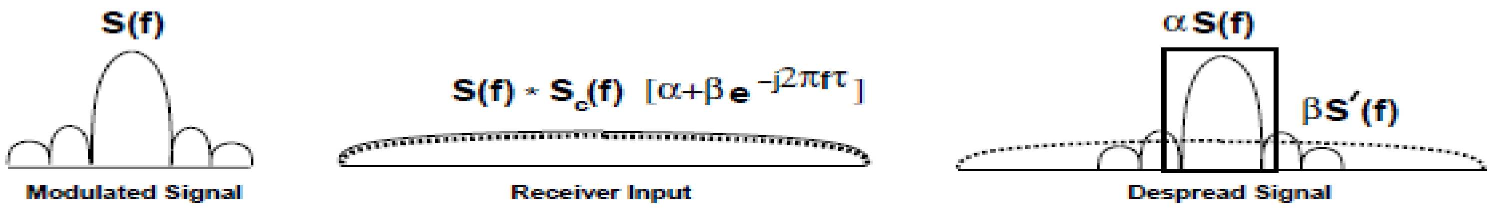

Figure 13.3: ISI Rejection in DSSS.

ISI rejection

- Since the second multipath component includes the product of asynchronized copies of $s_c(t)$, it remains spread out over the spreading code bandwidth
- the demodulation process will remove most of its energy
- If $\tau > T_c$ → significant mitigation of the ISI when the modulated signal is spread over a wide bandwidth
- Spreading code autocorrelation determines the ISI rejection of the spread spectrum system

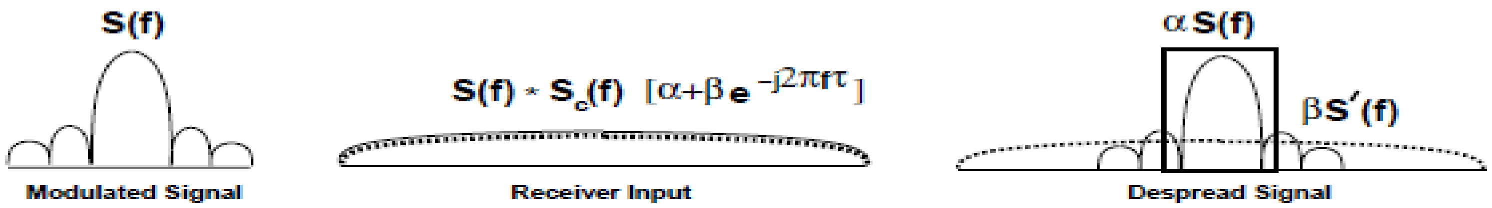

Figure 13.3: ISI Rejection in DSSS.

Frequency hopping spread spectrum (FHSS)

- To hop the modulated data signal over a wide bandwidth by changing its carrier frequency according to a spreading code $s_c(t)$.

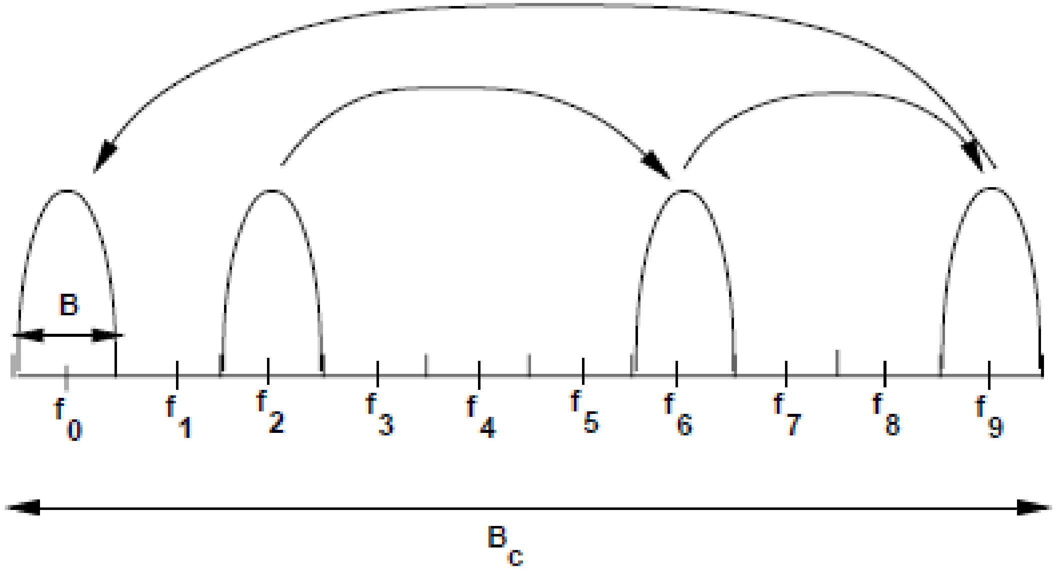

Figure 13.4: Frequency Hopping.

Frequency hopping spread spectrum (FHSS)

- The chip time T_c dictates the time between hops, i.e. the time duration over which the modulated data signal is centered at a given carrier frequency f_i before hopping to a new carrier frequency.
- The hop time can exceed a symbol time, $T_c = kT_s$ for some integer k, which is called slow frequency hopping (SFH),
- or the carrier can be changed multiple times per symbol, $T_c = \frac{T_s}{k}$ for some integer k, which is called fast frequency hopping (FFH)

Frequency hopping spread spectrum (FHSS)

- In FFH there is frequency diversity on every symbol, which protects each symbol against narrowband interference and spectral nulls due to frequency-selective fading
- The bandwidth of the FH system is approximately equal to NB, where N is the number of carrier frequencies available for hopping and B is the bandwidth of the data signal.
- The signal is generated using a frequency synthesizer that determines the modulating carrier frequency from the chip sequence (typically using FM modulation)
- In the receiver, the signal is demodulated using a similar frequency synthesizer synchronized to the chip sequence $s_c(t)$, that generates the sequence of carrier frequencies from this chip sequence
- Like DSSS, FH has no impact on performance in an AWGN channel, but mitigates the effects of narrowband interference and multipath

Frequency hopping spread spectrum (FHSS)

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- **Narrowband interference (bandwidth B at carrier fi) mitigation**
- If the hop sequence spends an equal amount of time at each of the carrier frequencies, then interference occurs a fraction $1/N$ of the time, and thus the interference power is reduced by roughly $1/N$
- DS results in a reduced-power interference all the time, whereas FHSS has a full power interferer a fraction of the time
- In FFH, systems the interference affects only a fraction of a symbol time, so coding may not be required to compensate for this interference
- Coding with interleaving may be used in SFH to avoid many simultaneous errors in a single codeword.
- FH is commonly used in military systems (interferers are jammers!!!)

Frequency hopping spread spectrum (FHSS)

- **ISI mitigation**
- For two-path channel multipath component with delay τ,
- the receiver synchronizes to the hop sequence associated with the LOS signal path
- Then the LOS path is demodulated at the desired carrier frequency
- if $\tau > T_c$, the receiver will have hopped to a new carrier frequency $f_j \neq f_i$, since the multipath occupies a different frequency band than the LOS signal component being demodulated, it causes negligible interference to the demodulated signal
- the demodulated signal does not exhibit either flat or frequency-selective fading (negligible interference) for $\tau > T_c$

Frequency hopping spread spectrum (FHSS)

- **ISI mitigation**
- For $\tau < T_c$, the impact of multipath depends on the bandwidth B of the modulated data signal as well as the hop rate
- an FFH system ($\tau < T_c \ll T_s$) will exhibit flat fading
- an SFH system, all the multipath will arrive while the signal is at the same carrier frequency, so the impact of multipath is the same as if there were no frequency hopping
- SFH will exhibit <u>slowly varying flat fading</u> for $B < 1/\tau$ and <u>slowly varying frequency-selective fading</u> for $B > 1/\tau$

Multiuser capability

- Both DSSS and FHSS provide a mechanism for multiple access
- Many users can simultaneously share the spread bandwidth with minimal interference between users
- The interference between users is determined by the cross-correlation of their spreading codes
- Spreading code designs typically have either good autocorrelation properties to mitigate ISI or good cross-correlation properties to mitigate multiuser interference
- Frequency hopping has some benefits over direct sequence in multiuser systems
- Used in cellular systems to average out interference from other cells

Multiuser capability

- Ex: Consider an SFH system with hop time Tc = 10 μsec and symbol time Ts = 1 μ sec. If the FH signal is transmitted over a multipath channel, for approximately what range of multipath delay spreads will the received despread signal exhibit frequency-selective fading?

Multiuser capability

- *Solution:*
  - Based on the two-path model analysis, the signal only exhibits fading, flat or frequency-selective, when the delay spread $\tau < Tc = 10\ \mu$sec.
  - Moreover, for frequency-selective fading we require $B \approx \frac{1}{Ts} = 10^6 > 1/\tau$, i.e. we require $\tau > 10^{-6} = 1\mu$sec.
  - So the despread signal will exhibit frequency-selective fading for delay spreads ranging from approximately 1 to 10 μsec.

DSSS System model

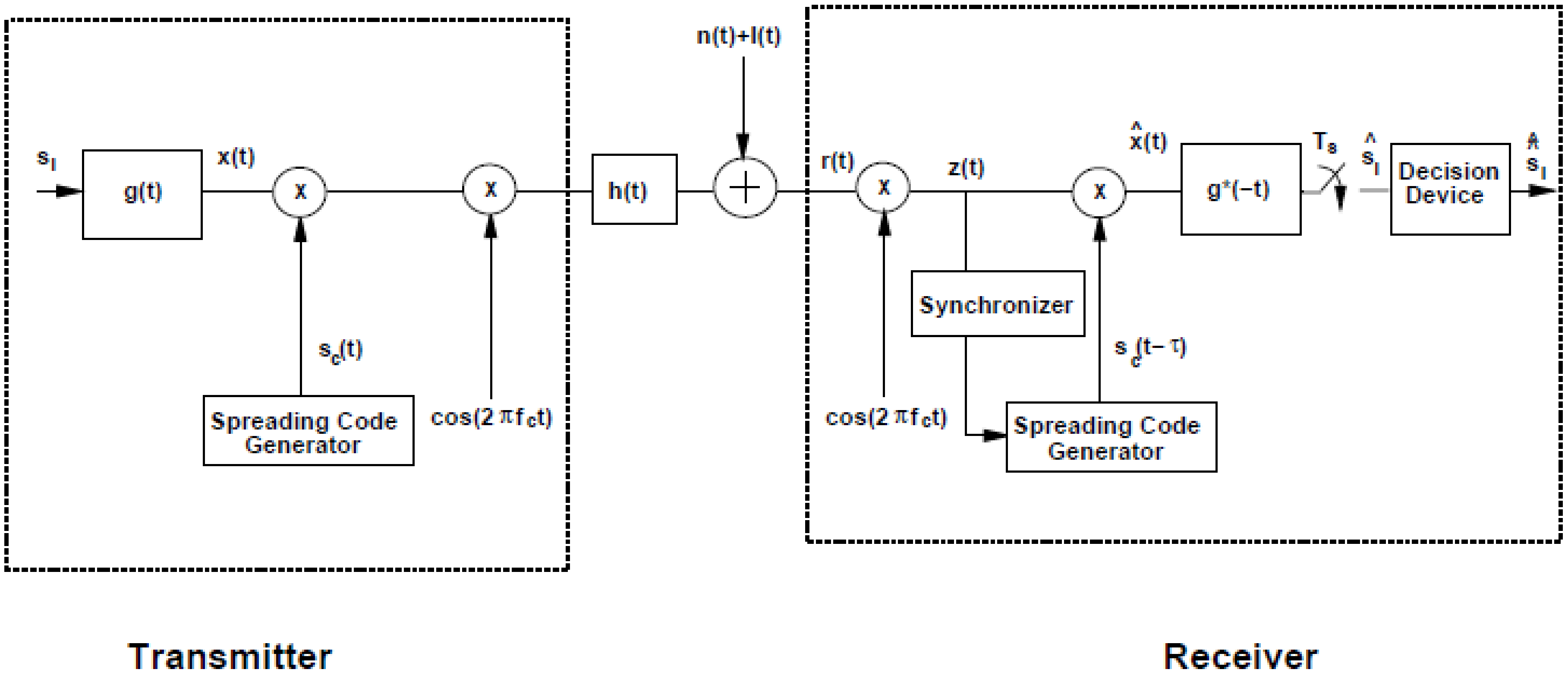

Figure 13.5: DSSS System Model

Spreading codes generation

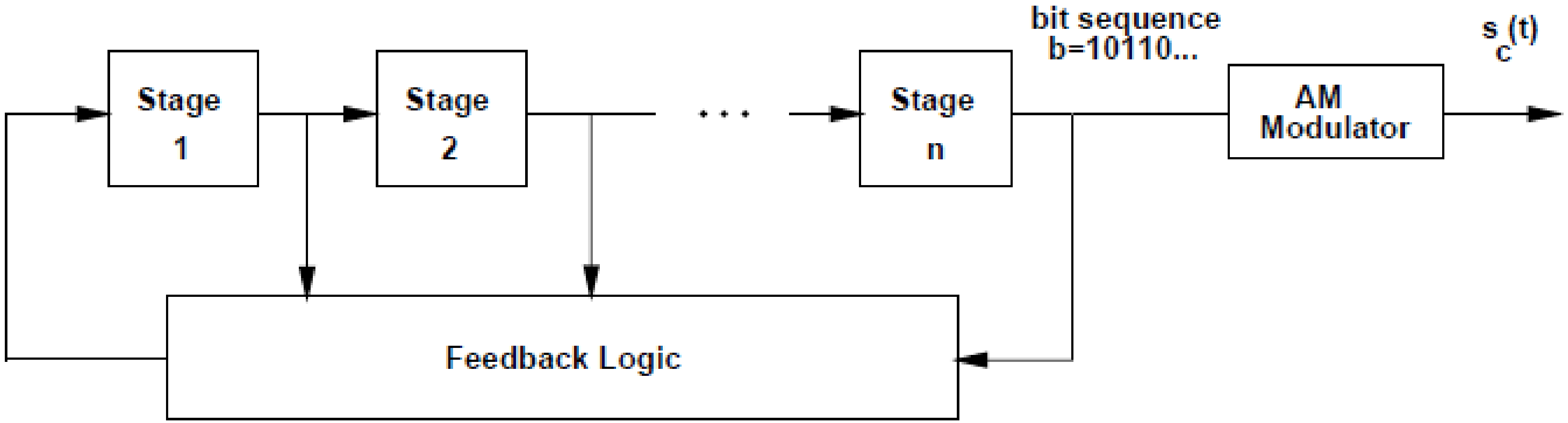

Figure 13.6: Generation of Spreading Codes

Pseudo-random sequence properties

- Deterministic (so it is pseudo-random)
- consists of i.i.d. bit values with probability one half for a one or a zero (balanced property/ to avoid DC component)
- of length *N*
- the run length in such sequences is generally short (a fraction $1/2^r$ of all runs are of length *r*) → run length property
- if they are shifted by any nonzero number of elements, the resulting sequence will have half its elements the same as in the original sequence, and half its elements different from the original sequence (shift property)

RAKE receivers

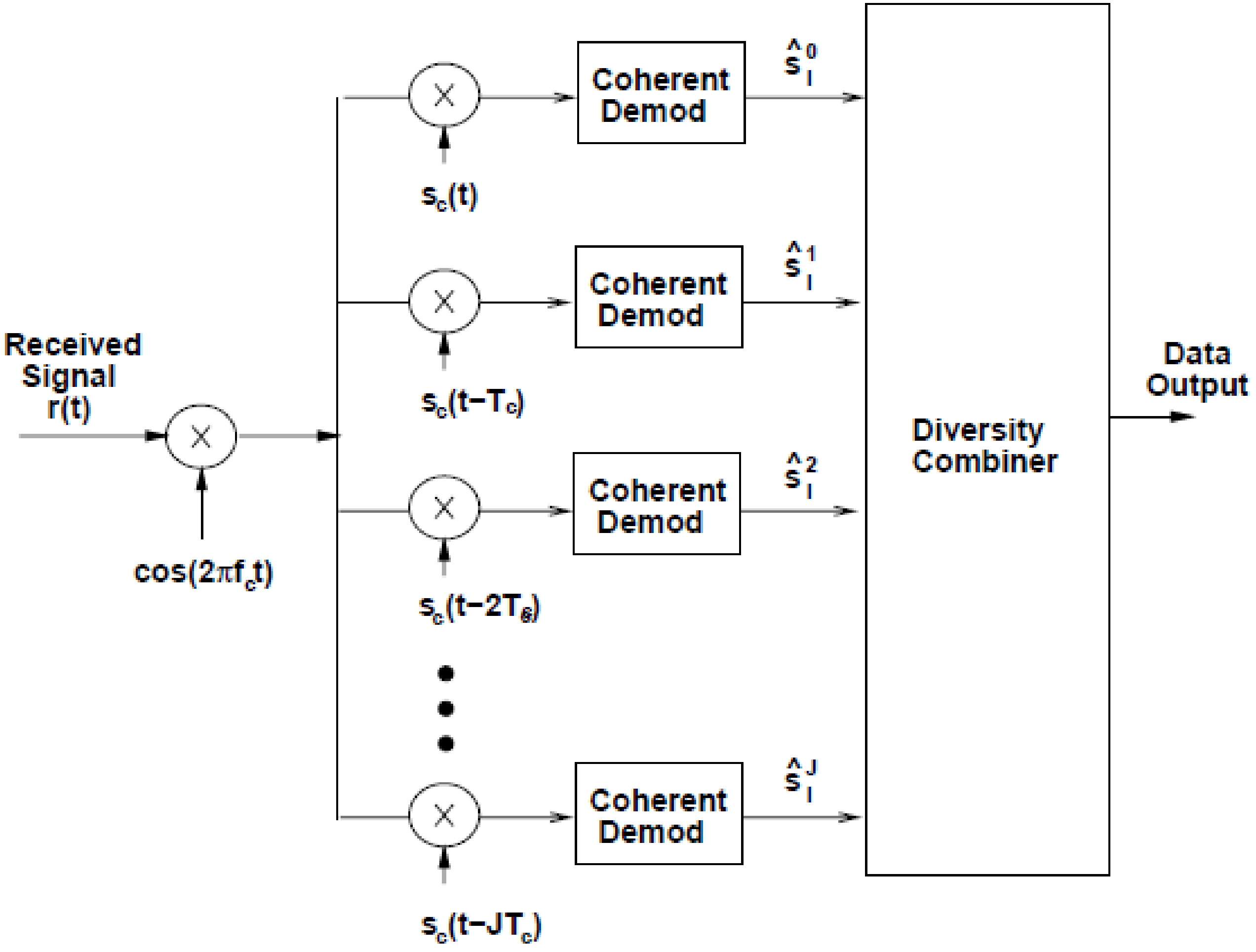

Figure 13.10: RAKE receiver

FHSS system model

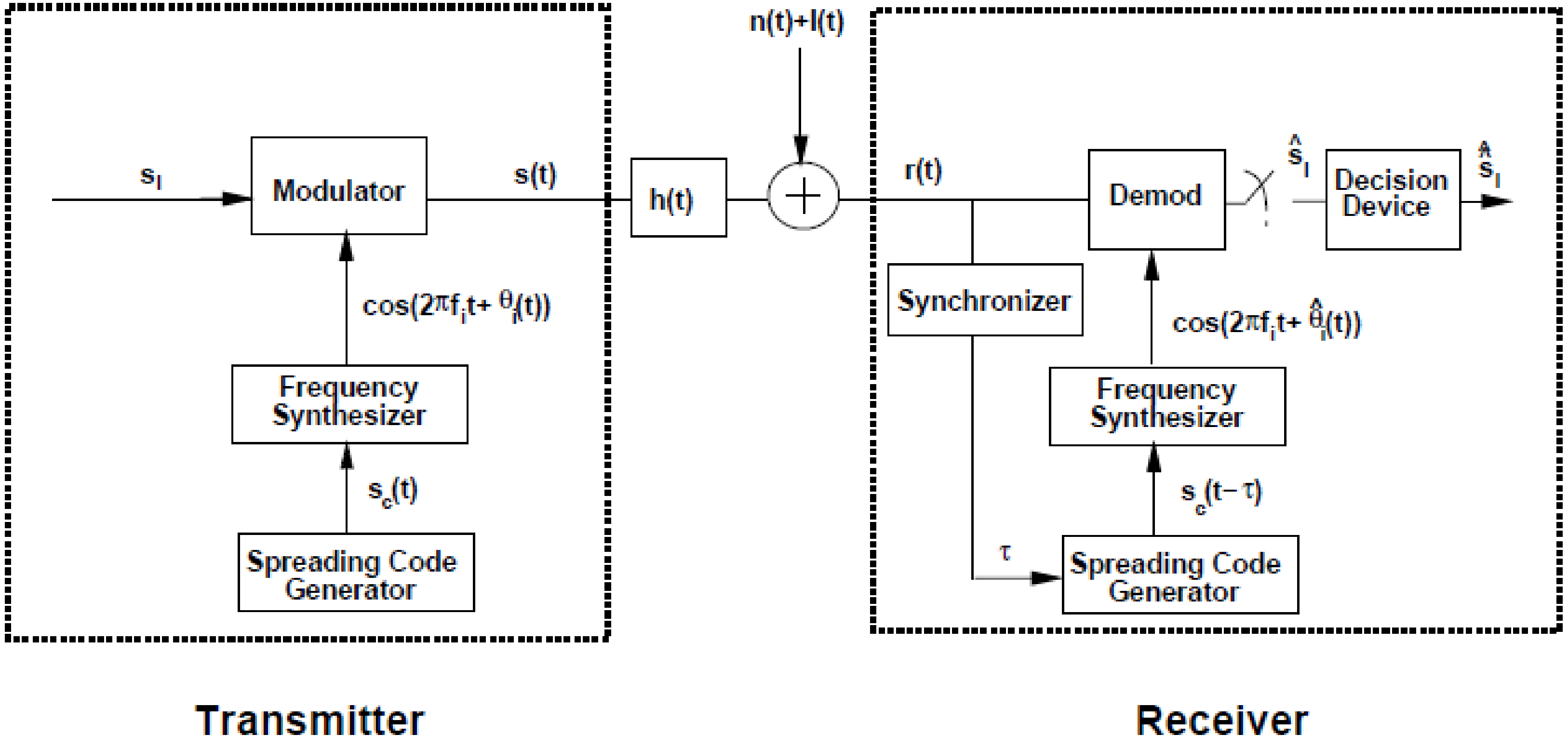

Figure 13.11: FHSS System Model

Multiuser DSSS Systems

- Spread spectrum can also be used as a mechanism for many users to share the same spectrum
- Using spreading code properties to support multiple users within the same spread bandwidth is also called spread-spectrum multiple access (SSMA), which is a special case of code-division multiple access (CDMA)
- In multiuser spread spectrum, each user is assigned a unique spreading code or hopping pattern, which is used to modulate their data signal.
- spreading codes or hopping patterns can be orthogonal/non-orthogonal
- spread spectrum multiuser systems can support an equal or larger number of users in a given bandwidth than other forms of spectral sharing such as time-division or frequency-division.

Multiuser DSSS Systems

- the most common chip sequences and their associated spreading codes that are used in multiuser DSSS systems:
  - **Gold Codes (used in GPS)**
  - **Kasami Codes**
  - **Walsh-Hadamard Codes**